Journal of Quantitative Spectroscopy & Radiative Transfer 187 (2017) 511–522

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Two-dimensional radiative transfer for the retrieval of limb emission measurements in the martian atmosphere

Armin Kleinböhl *, A. James Friedson, John T. Schofield

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA

ARTICLE INFO

Article history:
Received 5 May 2016
Received in revised form
13 July 2016
Accepted 13 July 2016
Available online 25 July 2016

Keywords:
2D
Radiative transfer
Limb geometry
Mars
MCS

ABSTRACT

The remote sounding of infrared emission from planetary atmospheres using limb-viewing geometry is a powerful technique for deriving vertical profiles of structure and composition on a global scale. Compared with nadir viewing, limb geometry provides enhanced vertical resolution and greater sensitivity to atmospheric constituents. However, standard limb profile retrieval techniques assume spherical symmetry and are vulnerable to biases produced by horizontal gradients in atmospheric parameters. We present a scheme for the correction of horizontal gradients in profile retrievals from limb observations of the martian atmosphere. It characterizes horizontal gradients in temperature, pressure, and aerosol extinction along the line-of-sight of a limb view through neighboring measurements, and represents these gradients by means of two-dimensional radiative transfer in the forward model of the retrieval. The scheme is applied to limb emission measurements from the Mars Climate Sounder instrument on Mars Reconnaissance Orbiter. Retrieval simulations using data from numerical models indicate that biases of up to 10 K in the winter polar region, obtained with standard retrievals using spherical symmetry, are reduced to about 2 K in most locations by the retrieval with two-dimensional radiative transfer. Retrievals from Mars atmospheric measurements suggest that the two-dimensional radiative transfer greatly reduces biases in temperature and aerosol opacity caused by observational geometry, predominantly in the polar winter regions.

1. Introduction

Limb-sounding is a powerful technique for investigating the structure and composition of atmospheres. By measuring radiation at various tangent altitudes one can typically obtain improved vertical resolution and, due to the long optical path, increased sensitivity in comparison to a nadir-viewing measurement. However, the long atmospheric path length makes limb-viewing measurements also susceptible to horizontal gradients and inhomogeneities in the atmosphere, which can affect the accuracy of the geophysical quantities that are retrieved from these measurements.

The importance of gradients along the line-of-sight (LOS) of a limb measurement was recognized during the development of large limb-sounding experiments designed to study Earth's atmospheric composition at microwave and infrared wavelengths [1–3]. Several largely independent studies suggested corrections and mitigation approaches for this problem. For the passive infrared sounder MIPAS onboard the satellite ENVISAT, several generations of two-dimensional limb retrieval algorithms were developed [4–7]. A similar approach was studied by Worden et al. [3] for the Thermal Emission Spectrometer (TES) onboard the EOS-AURA satellite. These algorithms take advantage of the atmospheric emission being continuously measured along the orbit track. The overlap of adjacent measurements then provides information on the lateral distribution of the measured quantity. Kiefer et al. [8] showed that inhomogeneities in the temperature field, and possibly in the fields of the measured trace species, can cause significant deviations between the results of a one-dimensional (1D) retrieval and a fully tomographic two-dimensional (2D) retrieval of MIPAS measurements. They suggest that including an appropriate temperature gradient in the forward model of a 1D retrieval helps to reduce these differences.

For the Microwave Limb Sounder (MLS) experiment on EOS-AURA a 2D retrieval approach has been included in the operational retrieval algorithm [9]. It divides the data along the orbit into slightly overlapping sets of typically 15° of great circle arc length [1]. Two-dimensional retrievals are performed independently on each set. Atmospheric profiles from the center region of each set are then selected for archiving. In the visible wavelength region 2D retrieval algorithms are used to retrieve nitric oxide [10] and metal concentrations [11] in the mesosphere/lower thermosphere region from measurements of the atmospheric spectrometer SCIAMACHY onboard ENVISAT. Recently, a 3D tomographic approach has been suggested for retrievals from an airborne limb-imaging instrument [12,13].

* Corresponding author.

http://dx.doi.org/10.1016/j.jqsrt.2016.07.009
0022-4073/

Due to the lack of suitable data sets, 2D radiative transfer and retrievals have rarely been applied to planetary atmospheres. The only example known to the authors is the retrieval of temperatures in the atmosphere of Titan from measurements by the Composite Infrared Radiometer-Spectrometer (CIRS) on the Cassini spacecraft [14]. They analysed limb measurements with the spacecraft located near the equatorial plane of Titan, leading to ray paths with a largely zonal orientation for equatorial measurements but with a significant meridional component towards higher latitudes. Application of a 2D retrieval approach hence suggested significant improvements in accuracy for higher latitude measurements because of large latitudinal temperature gradients in Titan's polar regions. Two approaches were examined: In the first a 2D forward model was used. Retrievals for higher latitudes used temperatures from previous retrievals from lower latitudes in order to prescribe the temperature variations with latitude between the tangent point and the spacecraft along the LOS. In the second approach atmospheric parameters at all latitudes and altitudes were retrieved simultaneously from an entire measurement sequence that spanned the range from equatorial to polar latitudes. It was found that the two approaches gave similar results and the second approach was implemented for retrievals of atmospheric temperatures on Titan from CIRS [14,15].

Here we develop a 2D radiative transfer scheme for orbital limb emission measurements in the infrared, and apply it to retrievals of temperature, dust and water ice opacity in the atmosphere of Mars from measurements by the Mars Climate Sounder (MCS). The approach is related to the aforementioned first approach by Achterberg et al. [14] but makes use of continuous measurement coverage along the orbit track. The approach was selected as a straight forward expansion of the current MCS radiative transfer and retrieval algorithm, which is designed to run in an operational environment [16]. MCS [17] is a passive infrared radiometer onboard Mars Reconnaissance Orbiter (MRO), which views the martian atmosphere in limb, nadir, and off-nadir geometries. It has 5 mid-infrared, 3 far infrared, and one broadband visible/near-infrared channel. Each spectral channel uses a linear detector array consisting of 21 elements, which provides −10 to 90 km altitude coverage with 5 km vertical sampling when pointed at the Mars limb. Profiles of temperature, dust and water ice extinction are simultaneously retrieved from the radiance measurements in an operational setup. Retrievals use a modified Chahine method together with a Curtis-Godson approximation in the radiative transfer [16] and employ a single-scattering approximation to account for scattering in the limb radiative transfer [18]. The mid-infrared channels A1, A2, and A3 cover frequencies within the 15 μm gaseous absorption band of CO_2, the main consituent of the martian atmosphere. As the atmospheric mixing ratio of CO_2 is known, these channels are used for the retrieval of temperature. Temperature retrievals are based on a combination of co-located limb and nadir/off-nadir measurements [19], which improves coverage at low altitudes. They also include the retrieval of surface brightness temperature at 32 μm using the B1 channel in nadir or off-nadir geometry. Aerosol extinction retrievals are based on limb measurements in channel A4, centered on a water ice absorption feature at 12 μm, and channel A5, covering an absorption feature of Mars dust around 22 μm.

MRO is in a sun-synchronous polar orbit at an altitude of about 250–320 km above the Mars surface, with equator crossings close to 3 AM and 3 PM local time and the ascending node on the dayside part of the orbit [20]. In standard operations, MCS views the forward limb along the orbit track. These in-track measurements are designed to give full latitudinal coverage and make 2D radiative transfer possible in the profile retrieval process. The 2D effect is expected to be particularly important in polar winter regions due to strong latitudinal temperature gradients in the atmosphere [21,22]. In fact, initial temperature retrievals by MCS in the south polar winter suggested that the cold pole of the polar vortex was systematically offset from the geographic pole towards the dayside part of the MRO orbit (Figure 1 of [21]). In addition, temperature profiles between 75 °S and 70 °S at a season of $L_s = 130° – 140°$ seemed to separate into two families around 20 km altitude (Figure 2a of [21]), one following the CO_2 frost point very closely and the other being several K warmer. The top left panel of Fig. 1 shows temperature profiles retrieved from the same set of measurements with the current 1D retrieval algorithm. The color coding separates the retrievals on the dayside from the retrievals on the nightside parts of the orbit. Although latitudes poleward of 70 °S do not receive any heating from direct sunlight at this season, there is a systematic temperature difference between profiles on the dayside and the nightside parts of the orbit at altitudes corresponding to pressures higher than ~5 Pa. Where temperature averages at both daytime and nighttime parallel the CO_2 frost point, the nighttime average is about 8 K warmer than the daytime average. Systematic differences between daytime and nighttime are also found in the retrieved water ice opacity at this season (top right panel in Fig. 1). The bottom panel of Fig. 1 shows profile retrievals of temperature and water ice opacity in the northern polar region at the opposite season. The differences between the averaged temperature profiles on the dayside and nightside parts of the orbit are even larger than in the southern polar region and can reach ~30 K around 20 Pa. Differences in retrieved water ice opacity between daytime and nighttime are also more pronounced. Note that in the northern polar region the nighttime temperatures are colder than the daytime temperatures, while in the southern polar region the temperatures from the daytime part of the orbit are colder than the ones from the nighttime part. This is consistent with the differences between daytime and nighttime in the retrieved temperatures being largely related to viewing geometry, rather than actual atmospheric characteristics. In limb emission measurements not all radiance originates around the tangent point. Significant radiance contributions originate along the LOS between the tangent point and the instrument (see e.g. Figure 12 in [16]). When taking limb measurements of the nighttime south polar vortex region (daytime north polar vortex region) the instrument is located above the vicinity of the vortex edge looking into the cold polar vortex. Hence radiance contributions between the tangent point and the instrument are likely to be underestimated with a radiative transfer that assumes spherical symmetry, leading to a high bias in the retrieved temperature. In contrast, when taking limb measurements of the daytime south polar vortex region (nighttime north polar vortex region) the instrument is located above the polar vortex looking out. Radiance contributions between the tangent point and the instrument are likely to be overestimated, leading to a low bias in the retrieved temperature.

There is a strong interest in the dynamics of the martian polar vortices as they are strongly connected to the zonal [23,24] and meridional atmospheric circulation [21,25], and influence travelling waves [26] as well as tides [27]. Further interest has recently developed concerning aerosol in the polar regions, in particular water ice [28,29] and CO_2 ice condensates [30,31], the latter having a strong influence on the polar radiative balance and the formation of the polar ice caps. Studies of these kinds would benefit from MCS temperature and aerosol retrievals with improved accuracy in the polar regions through the consideration of 2D effects. The development of this data set is the topic of this paper. We discuss our approach and its implementation in Section 2. We evaluate our algorithm by retrieving atmospheric parameters from simulated radiances in Section 3. We show results of retrievals with 2D radiative transfer applied to actual MCS measurements in Section 4. We summarize key features and findings in a conclusion section.